

Reconnection of Magnetic Fields:

Magnetohydrodynamics and Collisionless Theory and
Observations

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Reconnection in the Magnetosphere

In this chapter we focus particularly on recent advances in observations and simulations of reconnection at the magnetopause and in the *near magnetotail*, as these are the sites most heavily investigated by observations and simulations. The scenarios at the two sites have characteristic differences. At the magnetopause, reconnection occurs between two topologically distinct regions, the shocked solar wind and the magnetosphere, which also have quite different plasma properties. Reconnection generates a magnetic field component normal to the magnetopause and thereby leads to an interconnection between the two regions. As discussed in Section 1.2 and further in 4.5, magnetopause reconnection may have quasi-stationary features (as indicated in Figure 1.2) as well as features that indicate localized, temporally limited reconnection, (FTEs, Russell and Elphic, 1978; Elphic, 1995, Figure 1.5). Critical parameters in reconnection at the magnetopause are the magnitude of the magnetic field component in the direction of the magnetopause current (*guide field*), the angle between the magnetic fields on either side of the current sheet, and the plasma properties, all of which may play a role in when and where and how reconnection takes place. Major questions of magnetopause reconnection, to be addressed in Sections 4.1 and 4.2, concern the location of reconnection sites and the temporal variability of the process under different solar wind conditions, both of which may be related to the role of a guide field.

In contrast to magnetopause reconnection, reconnection in the near tail takes place in a current sheet that already contains a magnetic field component normal to the current sheet, and the reconnecting field lines, at least initially, are not topologically distinct. (This changes when reconnection proceeds to lobe field lines.) As discussed in Section 3.3, the critical question here is not the role of a guide field, which tends to be quite small on average, but rather whether and how the normal field component B_z can become reduced to overcome its stabilizing effect. In Section 4.3 we continue the discussion of magnetotail stability, based on recent investigations of ideal MHD stability of 2D equilibria and of the collisionless tearing mode.

The stability discussion is followed by results from large-scale theory and simulations, concerning current sheet formation and the consequences of reconnection in the magnetotail (Section 4.4), which also includes the effects on currents and particles. Although major features of magnetic reconnection in the magnetotail have been discovered by single satellites or the two *International Sun Earth Explorer* (ISEE 1 and 2) spacecraft, particular progress has been made recently by the four-satellite

Cluster mission, which for the first time permitted the calculation of spatial gradients without model assumptions. These observations form the particular focus of Section 4.5. The chapter is completed in Section 4.6 by remote sensing observations, which provide a unique way of determining reconnection rates without in situ information.

4.1 Simulations of reconnection at the magnetopause

J. C. Dorelli

4.2 Observations of magnetopause reconnection

K. J. Trattner, S. A. Fuselier, and S. A. Petrinec

4.3 Stability of the magnetotail

K. Schindler

4.4 Simulations of reconnection in the magnetotail

J. Birn

4.5 Observations of tail reconnection

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Because of the difficulty of separating temporal variations and spatial structure in a highly dynamic system, measurements with a single spacecraft have always been problematic and lead to debate. This was especially true when trying to explore the site of reconnection in the near-Earth magnetotail. While sophisticated and detailed studies of this region using data from the Geotail spacecraft (e.g., Nagai et al., 1998, 2001, 2003) revealed some of its internal structure, some ambiguity still prevailed.

In this section we will report on the present state of investigating reconnection in the vicinity of the near-Earth neutral line based on recent *Cluster* measurements. Being a constellation of four identical spacecraft, *Cluster* allows discrimination of spatial and temporal variations in magnetic field and plasma parameters. Thus it is ideal to study the structure and dynamics of plasma and fields relevant to reconnection. In this section we first present an example of multi-point observation of current sheet crossings near the X-line and discuss the effects of unmagnetized ions including the Hall-current. We then discuss the closure of the Hall-current, followed by a brief discussion of new results on the consequences of reconnection such as bursty bulk flows, plasmoids, and slow-mode shocks.

4.5.1 *Cluster tetrahedron*

The *Cluster* spacecraft have been launched in summer 2000 and put into a polar orbit with an apogee of about $19 R_E$. *Cluster* traverses the magnetotail from mid July to end October, crossing the plasma sheet in a nearly regular tetrahedron form. The typical configuration of the *Cluster* tetrahedron during the 2001 tail season is shown in Fig. 4.1. Most of the *Cluster* data discussed here were obtained by the Flux-Gate Magnetometer (FGM; Balogh et al., 2001) and by the *Cluster* Ion Spectrometry (CIS; Rème et al., 2001) unless noted otherwise.

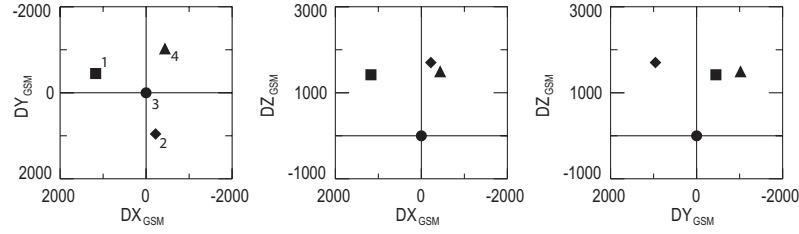


Fig. 4.1. Typical Cluster tetrahedron configuration during the 2001 tail season

4.5.2 Current sheet structure

Spacecraft travelling in the plasma sheet often observe rapid large amplitude variations of the magnetic field, sometimes with a change of polarity (a change in the sign of the prevailing B_x component). Such variations indicate rapid up-down oscillations of the current sheet known as “flapping” (Zhang et al., 2002; Runov et al., 2003b; Sergeev et al., 2003, 2004). Being an interesting phenomenon itself, flapping provides a possibility to probe the internal structure of the current sheet.

Fig. 4.2 shows an example of current sheet crossings during an episode of intensive flapping. The top two panels on the left-hand side show the x component of the magnetic field at all four spacecraft (upper panel) and the proton bulk velocity (data from Cluster 1, 3 and 4 only) observed during a large storm-time substorm on October 1, 2001. A set of rapid current sheet crossings during intervals A - D were used to reconstruct the structure of magnetic field and electric current inside the current sheet. The resulting current density $\mathbf{j} = \nabla \times \mathbf{B}/\mu_0$ and the magnetic field curvature vector $\mathbf{C} = (\mathbf{b} \cdot \nabla)\mathbf{b}$, where $\mathbf{b} = \mathbf{B}/B$, are shown in the two mid panels. The calculations show that the electric current was very strong (about 30 nA/m²) during intervals A, B, and C and less intense during interval D. The x component of the magnetic field curvature vector was dominant during all the crossings and reversals from negative to positive and vice versa indicate a complex magnetic field topology and the close encounter of a magnetic neutral line.

The panels on the right-hand side of Fig. 4.2 show the reconstructed spatial profiles of current density and magnetic field. The method of reconstruction is based on linear gradient estimation (Chanteur, 1998). It is supposed that during the flapping the current sheet is simply translated without any change of its structure and the streamline derivative $d\mathbf{B}/dt = \partial\mathbf{B}/\partial t + (\mathbf{U} \cdot \nabla)\mathbf{B} = 0$. Then integration of the translation velocity projected onto the local current sheet normal $U_n = \partial B_x / \partial t / \nabla_n B_x$ during the crossing gives an estimate for the vertical scale Z^* (see Runov et al., 2005b). The current density profiles have very similar shapes and show that during intervals A, B and C Cluster crosses a single-peaked thin current sheet with a half-thickness of about one ion gyro radius. The profile during interval D shows a change in the current sheet structure. Interval E, with reversals of the magnetic field curvature vector and ion bulk flow direction, will be discussed below.

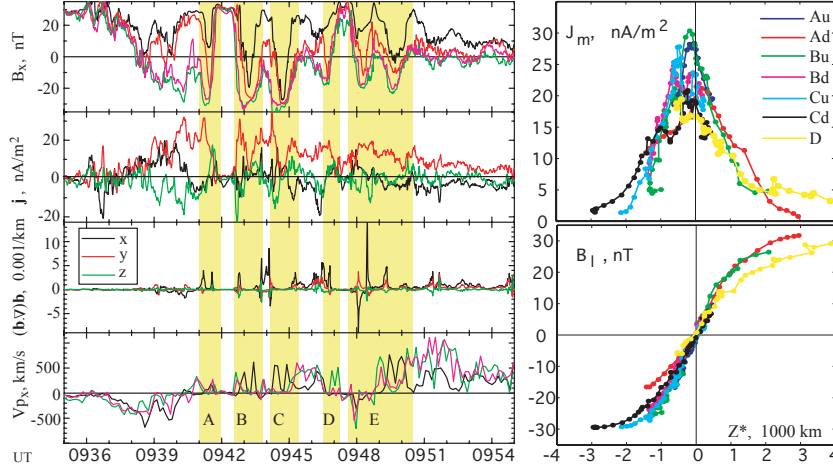


Fig. 4.2. Cluster observations during a flapping event on October 1, 2001 (left-hand panel): B_x from Cluster/FGM, components of the current density $\mathbf{j} = \nabla \times \mathbf{B}/\mu_0$, and the magnetic curvature vector $\mathbf{C} = (\mathbf{b} \cdot \nabla)\mathbf{b}$, and x component of the proton bulk velocity from Cluster/CIS. Reconstructed profiles of current density (cross-tail component) and maximum variance component of the magnetic field for current sheet crossing A – D (right-hand panel). Index u denotes upward motion of the sheet, B_x changes from positive to negative, and d indicates downward motion (from Runov et al., 2005a).

4.5.3 X-line encounter and Hall currents

During the repeated current sheet crossings in interval E in Fig. 4.2, Cluster observed a fast flow reversal from tailward, with a maximum speed of 800 km/s, to earthward, with maximum value of 700 km/s. The magnetic field curvature vector, calculated from four-point magnetic field observations (see also Shen et al., 2003), also reversed, first pointing tailward during the tailward flow, then earthward during the earthward flow. The corresponding reversals of the magnetic field curvature and proton bulk velocity indicate that Cluster crossed a tailward travelling magnetic X-line (Runov et al., 2003a).

Fig. 4.3 illustrates the situation. The three bottom rows show snapshots of the magnetic field and proton bulk velocity measured by Cluster at three consecutive instances, during which the X-line passes over the spacecraft. Two upper rows present a schematic view of the Cluster tetrahedron position fitted to a simulated magnetic field and ion flow around an X-line (adapted from Hoshino et al., 2001). Note that Cluster observations of the earliest times are plotted at the right, since the X-line moved tailward, or the location of Cluster relative to the X-line moved earthward.

At 0948:02 UT (right column) Cluster 1, 3 and 4 detected tailward flow. Cluster 1 and 2 detected earthward and dawnward ($B_y < 0$) magnetic field, while the magnetic field detected by Cluster 3 was tailward and duskward ($B_y > 0$). Cluster 4, staying closest to the neutral sheet, saw a very weak magnetic field, directed tailward and duskward. Cluster 2, 3 and 4 found a weakly negative B_z . Since the weakly positive B_z at Cluster 1 seems to be a short-lived (5 s) fluctuation (the average value during

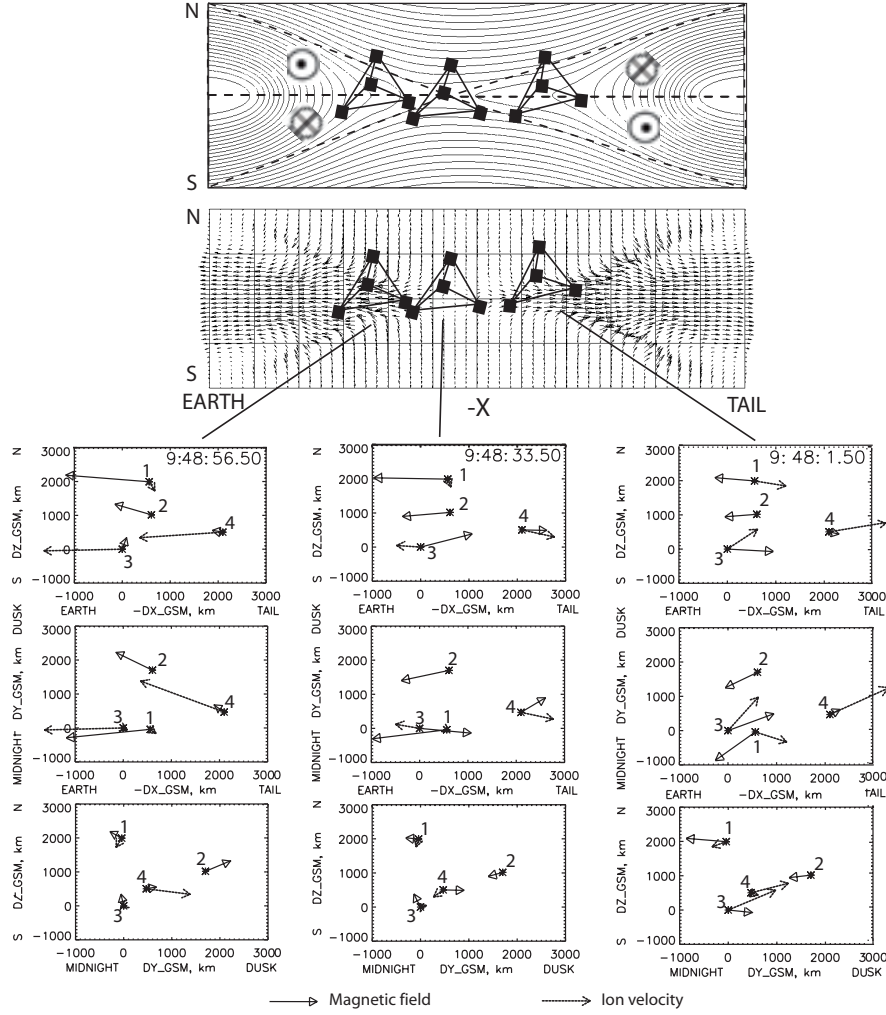


Fig. 4.3. Cluster observations of the magnetic X-line. Bottom panels: Snapshots of magnetic field and ion bulk velocity vectors in three GSM projections. The two upper figures are sketches of spacecraft positions with respect to the X-line, using magnetic field lines and ion velocity vectors from a simulation by Hoshino et al. (2001). The symbols \odot and \otimes give the direction of the B_y component (after Runov et al., 2005a).

the tailward flow (0947 - 0949 UT) is -2 nT), these data show that Cluster was located tailward of the X-line.

At 0948:34 UT (mid column) the pair of spacecraft most separated along x (Cluster 3 - 4) detected oppositely directed ion flow: Cluster 4 saw tailward and Cluster 3 earthward flow. Cluster 1, staying in a stronger magnetic field, observed slower ion flow directed mostly southward. The magnetic field topology also changed drastically: Cluster 1, 2 and 3 observed a magnetic field directed downward in the y, z plane (bottom row), while Cluster 4 saw the field directed duskward. Thus, the

separatrix apparently was located in between Cluster 4 and the other three: Cluster probed the close vicinity of the X-line. Since B_z at Cluster 1 and 3 was positive, while Cluster 2, separated along the y direction, showed a small negative B_z , the magnetic field around the X-line was highly non-uniform in all three directions and the typical scales were comparable to the Cluster separation. Cluster 2 and 3, separated by 1000 km along z detected almost equal magnitude but oppositely directed B_x , which roughly yields a current sheet half-thickness of about 500 km near the X-line.

At 0948:57 UT Cluster 3 and 4 observed strong earthward flow, while the flow detected by Cluster 1 was southward and much weaker. All four spacecraft detected a positive z component of the magnetic field. At the same time, the magnetic field observed by Cluster 1 had a dawnward component, while observations by Cluster 2 and 4 showed a duskward magnetic field component. The magnetic field from Cluster 3 was slightly dawnward and tailward.

The B_y observations can be interpreted as the observation of the Hall quadrupolar magnetic field structure (Section 3.1), first observed by Nagai et al. (1998) and schematically shown in the upper row of Fig. 4.3 and the sketch in Fig. 4.4 (after Runov et al., 2003a). Indeed, at 0948:02 UT, when Cluster was located tailward of the X-line, the two spacecraft (Cluster 1 and 2) staying in the northern hemisphere observed dawnward ($B_y < 0$) magnetic field, while the other two, situated in the southern hemisphere, detected $B_y > 0$. At 0948:34 the situation was more complex: Cluster 3 and 4, located in the southern hemisphere at opposite sides of the X-line detected oppositely directed out-of-plane magnetic fields (negative at Cluster 3 and positive at Cluster 4), which is consistent with the theoretical picture. Cluster 1, detecting the ion inflow, was likely located outside of the Hall zone. Cluster 2 was probably situated very close to the separatrix, where the Hall effect is negligible.

During the earthward flow interval (0948:57 UT) Cluster 2 and 4, staying in the northern hemisphere, showed $B_z > 0$, while Cluster 3 in the southern hemisphere detected $B_y < 0$, which is again consistent with the Hall reconnection model. Cluster 1, detecting ion inflow, was again located outside of the Hall current system region.

The quadrupolar out-of-plane magnetic field component is a manifestation of the Hall current system which has a direction opposite to the main flow direction indicated by the wide arrows in Fig. 4.4. The Hall currents result from ion-electron decoupling within the ion diffusion region with a characteristic scale of the ion inertial length (Section 3.2). These signatures were previously detected by Geotail (Nagai et al., 2001; Asano et al., 2004) and Wind (Øieroset et al., 2001) spacecraft, however, simultaneous multi-point observations by Cluster show, for the first time, the spatial structure of the Hall region.

4.5.4 Bifurcated current sheets

Nakamura et al. (2002b), using Cluster four-point measurements, found that the magnetotail current sheet sometimes exhibits a double-peaked profile of the electric current density. Such bifurcated current sheets may exist during intervals of high-speed ion flow (Runov et al., 2003a) as well as during intervals with $|V_x| \leq 100$ km/s (Sergeev et al., 2003; Asano et al., 2005). Their thickness varies from about $1 R_E$ (Runov et al., 2004) down to less than 1500 km (Asano et al., 2005).

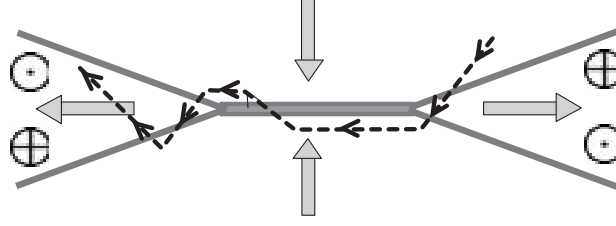


Fig. 4.4. Sketch of Cluster observations of Hall magnetic fields and current sheet structure around the reconnection region, the dashed line indicates the trajectory of Cluster, the symbols \odot and \otimes indicate the direction of the Hall magnetic fields, and the wide arrows show the main plasma flow direction. After Runov et al. (2003a).

The existence of thin bifurcated sheets may be closely associated with the formation of thin embedded current sheets at small scales (see also Section ??) prior to or during reconnection. Indeed, Runov et al. (2003a), analyzing the current sheet structure around the X-line encounter in interval E in Fig. 4.2, showed that during the tailward and earthward flow intervals the current sheet was bifurcated, with broad “valleys” between peaks of the current. The scale of the valleys was approximately 3000 - 4000 km. In between the oppositely directed flows the current sheet was very thin, with a half-thickness of 500 km, and had a flat profile near the maximum of the current ($\sim 20 \text{ nA/m}^2$). This is depicted schematically in Fig. 4.4.

4.5.5 Hall current closure

The Hall currents generated in the ion diffusion require continuation currents outside the ion diffusion region. At the lobe side, the closure of the Hall currents takes place via cold electrons flowing into the ion diffusion region. At the outflow region, on the other hand, accelerated electrons exiting along the magnetic field provide currents into the ion diffusion region. Such behavior of the electrons has been observed previously by Geotail (Fujimoto et al., 2001; Nagai et al., 2001) and by Wind space craft (Øieroset et al., 2001). These field-aligned currents can be observed also well outside the reconnection region. In particular, at the earthward side of the reconnection region, they may even extend to the auroral acceleration region (Treumann et al., 2005). Cluster also observed such downward-upward field-aligned current pairs associated with a transient encounter of energetic ion beams, which suggests a connection to the ion diffusion region as illustrated in Fig. 4.5 (adapted from Nakamura et al., 2004b). Multi-point observations suggested that the scale size of the downward current was at maximum comparable to the ion inertia length so that it plausibly connects to the near-Earth X-line and is driven by Hall effects in the reconnection region as proposed by Fujimoto et al. (2001). Consistent with the electric field found in the vicinity of the ion diffusion region (Nagai et al., 2003), southward electric field ($-\mathbf{V} \times \mathbf{B}$ field from the drift of cold ions) was observed at Cluster. The observation also support the theoretical prediction (Treumann et al., 2005) that the downward current region is thin because on the lobe side, the ions may travel a substantial fraction of the ion inertia length until their motion separates from that of the electrons.

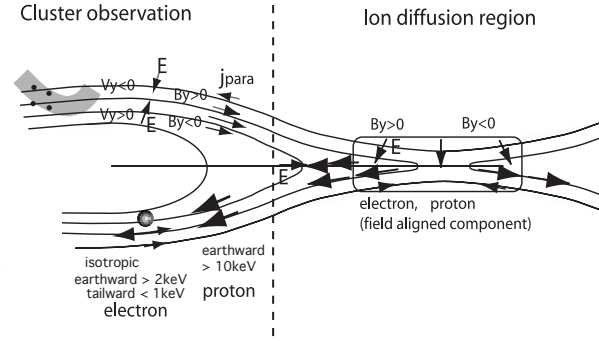


Fig. 4.5. Summary of observations by Cluster during a transient entry into the plasma sheet between 1240 and 1241 UT on October 10, 2001 substorm event (left hand side) and illustration of possible relationship to the reconnection region. For Cluster observations field signatures are showing in the northern hemisphere, while particle signatures are illustrated in the southern hemisphere assuming they are symmetric in hemisphere (adapted from Nakamura et al., 2004a)

The field-aligned current system closing the Hall current near the reconnection region has also been inferred using the electron moments from Geotail observations (Asano et al., 2004). The Plasma Electron And Current Experiment (PEACE; Johnstone et al., 1997) onboard Cluster also succeeded to measure the field-aligned electron currents at the earthward side of the reconnection region (Alexeev et al., 2005). In addition to confirming the downward (towards the X-line) and upward (away from the X-line) field-aligned currents near the plasma sheet boundary and the plasma sheet side, respectively, as predicted from the closure of the Hall currents, their observations showed a layer of stronger downward currents at the interface between the downward and upward currents. These different layers of field-aligned currents could be due to two nested diffusion regions possibly related to the effect of the heavy ions (Alexeev et al., 2005). For the same event, even finer structures with temporal scales less than 1 sec were observed to be embedded in the inflowing field-aligned beams (Asano et al., 2005) based on the high-temporal resolution measurement of the 500 eV field-aligned electrons with the Electron Drift Instrument (EDI; Paschmann et al., 2001) onboard Cluster.

4.5.6 Other features

It is interesting to note, that an excitation of electrostatic waves with amplitudes ≤ 400 mV/m and frequencies varying from ion cyclotron to lower hybrid, and electrostatic solitary waves with amplitudes of 25 mV/m and much higher frequencies were observed during the reconnection event discussed in Section 4.5.3 (Fig. 4.3) between 0947 - 0951 UT (Cattell et al., 2002) by the Electric Field and Wave (EFW) instrument (Gustafsson et al., 2001). These waves may provide the dissipation needed for reconnection in an advanced stage.

Another important new observation for this reconnection event is the ion composition. During the thin current sheet interval, 0945 - 0955 UT, pressure as well as density was dominated by O^+ rather than H^+ (Kistler et al., 2005), which was in-

terpreted as being due to storm-time ion outflow from the ionosphere. In the O^+ ion dominated thin current sheet, the O^+ ions were found to carry about 5-10% of the cross-tail current (Kistler et al., 2005). Detailed analysis of the distribution function showed separate O^+ layers above and below the thin current sheet (Wilber et al., 2004). The O^+ in the reconnection region was suggested to experience a ballistic acceleration (Wygant et al., 2005) based on the observation of a large amplitude bipolar electric field (± 60 mV/m) observed by EFW directed normal to the current sheets for the same event. Cluster therefore opened up a new interesting topic to investigate from the observational point of view: the effect of the multi-component plasma in the reconnection.

4.5.7 *Consequences of tail reconnection*

One of the major consequences of reconnection is the generation of fast plasma flows, which for a long time have been used as the major indicator of the occurrence of reconnection and for the identification of the location of the reconnection site. Statistical analyses of Geotail ion flow measurements thus concluded, from a distinction between the substorm-related onset of tailward and earthward flows, that usually near-Earth reconnection starts in the tail region between $20 R_E$ and $30 R_E$ distance from the Earth (Nagai et al., 1998).

Plasma bulk acceleration might take place not only in the immediate vicinity of the reconnection site but also at slow shocks, which in the Petschek model (Section 2.1) extend outward from the diffusion region. Slow-mode shocks connected to the ion diffusion region have been identified in the tail by previous studies (e.g., Feldman et al., 1987; Øieroset et al., 2000) based on Walén analysis and checking Rankine-Hugoniot shock jump conditions. Using multi-composition plasma observation by Cluster, Eriksson et al. (2004) performed a similar analysis by taking into account also the contributions from oxygen ions during a substorm X-line event when Cluster observed fast tailward and earthward flows. The successful joint Walén and slow shock analysis of the tailward flows within the plasma sheet presented further evidence in favor of Petschek-type reconnection at distances $X_{GSM} > -19 R_E$ of the near-Earth magnetotail. The failure of both the Walén test and the Rankine-Hugoniot analysis of the earthward flow portion of the plasma flow reversal event were interpreted to be associated with the strong earthward gradient of the magnetic field in the inner magnetosphere.

Due to its apogee Cluster observes much more earthward high-speed flows than tailward flows. This enabled to obtain new results on consequences of reconnection at the earthward side of the X-line(s), namely earthward propagating southward then northward magnetic field disturbances related to plasmoids/flux rope (Slavin et al., 2003a; Zong et al., 2004), traveling compression regions (Slavin et al., 2003b) and nightside flux transfer events (Penz et al., 2004; Sergeev et al., 2004), analogous to features more commonly observed tailward of the reconnection site. Multi-point analyses by Cluster were used to measure the current density and check a force-free model (Slavin et al., 2003b) and energetic particle boundaries (Zong et al., 2004) to show the structures of the plasmoid/flux rope. Yet, since the plasma flows jetting toward the Earth are significantly influenced by the strong dipolar field and pressure gradient, it still remains unknown to what extent these structures can be treated as

motion of a stable structure in the analyses. Similar magnetic features were rather interpreted as transient profiles associated with a change in the reconnection rate at a remote X-line, allowing a determination the location of the X-line (Penz et al., 2004; Sergeev et al., 2004). Determination of the field topology would be a key to differentiate whether these structure are coming from a single X-line or signature of multiple X-lines.

The bursty bulk flows (BBFs) and related phenomena, which are attributed to local reconnection that is not necessarily substorm related (Section 1.2), were also intensively studied by Cluster spacecraft using multi-point observations. A statistical analysis was performed by (Nakamura et al., 2004a) to estimate the typical scale size of BBFs. It was suggested that the full width of the flow channel is on average 2–3 R_E in the dawn-dusk direction and 1.5–2 R_E in the north-south direction. Furthermore, BBFs were found to be accompanied by different types of magnetic field disturbances such as dipolarization (Nakamura et al., 2002a), low frequency wave activity (Volwerk et al., 2003, 2004), and turbulence (Vörös et al., 2003, 2004).

The role of reconnection and fast flows in substorms has been one of the key topic in the magnetosphere. Using Cluster, together with the other spacecraft and ground-based observations, several case studies obtained the reconnection processes to be the key processes leading to a major substorm onset (Baker et al., 2002; Sergeev et al., 2005), although multiple pseudobreakups preceding the major onsets complicate the determination of the cause and effect arguments of the initial disturbance. During a more simple isolated earthward flow burst event magnetosphere-ionosphere coupling processes were studied by conjugate dense ionospheric observations and obtained BBF- associated field-aligned and ionospheric current system (Grocott et al., 2004; Nakamura et al., 2005).

4.6 Remote sensing of reconnection

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